

Vacuum properties of open charmed mesons in a chiral symmetric model

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Abstract. We present a $U(4)_R \times U(4)_L$ chirally symmetric model, which in addition to scalar and pseudoscalar mesons also includes vector and axial-vector mesons. A part from the three new parameters pertaining to the charm degree of freedom, the parameters of the model are fixed from the $N_f = 3$ flavor sector. We calculate open charmed meson masses and the weak decay constants of nonstrange open charm D and strange open charm D_S . We also evaluate the (OZI-dominant) strong decays of open charmed mesons. The results are turn out to be in quantitative agreement with experimental data.

1. Introduction

Open charmed mesons, composite states of charm quark (c) and up (u), down (d), or strange (s) antiquark, were observed two years later than the discovery of the J/ψ particle in 1974. Since that time, the study of charmed meson spectroscopy and decays has made significant experimental [1, 2, 3] and theoretical process [4, 5, 6, 7]. We show in the present work that how the original $SU(3)$ flavor symmetry of hadrons can be extended to $SU(4)$ in the framework of a chirally symmetric model with charm as an extra quantum number. Note that, chiral symmetry is strongly explicitly broken by the current charm quark mass.

The development of an effective hadronic Lagrangian plays an important role in the description of the masses and the interactions of low-lying hadron resonances [8]. To this end, we developed the so-called extended Linear Sigma Model (eLSM) in which (pseudo)scalar and (axial-)vector $q\bar{q}$ mesons and additional scalar and pseudoscalar glueball fields are the basic degrees of freedom. The eLSM has already shown success in describing the vacuum phenomenology of the nonstrange-strange mesons [9, 10, 11, 12, 13]. The eLSM emulates the global symmetries of the QCD Lagrangian; the global chiral symmetry (which is exact in the chiral limit), the discrete C, P, and T symmetries, and the classical dilatation (scale) symmetry. When working with colorless hadronic degrees of freedom, the local color symmetry of QCD is automatically preserved. In eLSM the global chiral symmetry is explicitly broken by non-vanishing quark masses and quantum effects [14], and spontaneously by a non-vanishing expectation value of the quark condensate in the QCD vacuum [15]. The dilatation symmetry is broken explicitly by the logarithmic term of the dilaton potential, by the mass terms, and by the $U(1)_A$ anomaly.

In these proceedings, we present the outline of the extension of the eLSM from the three-flavor case to the four-flavor case including the charm quark [16, 17, 18]. Most parameters of our

eLSM are taken directly from Ref.[12] where the nonstrange-strange mesons were considered. There are only new three parameters pertaining to the charm degree of freedom. We compute open charmed meson masses, the weak decay constants of the pseudoscalar D and D_s mesons, and the (OZI-dominant) strong decays of open charmed mesons.

2. The $U(4)_R \times U(4)_L$ Linear Sigma Model

In Refs.[16, 17, 18], we presented the outline of the extension of the eLSM from the three-flavor case to the four-flavor case including charm quark. In this extension, we introduced the (pseudo)scalar and (axial-)vector meson fields in terms of 4×4 (instead of 3×3) matrices, which the charmed mesons appear in the fourth row and fourth column as follows: The matrix of pseudoscalar fields P (with quantum numbers $J^{PC} = 0^{-+}$) reads

$$P = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\eta_N + \pi^0) & \pi^+ & K^+ & D^0 \\ \pi^- & \frac{1}{\sqrt{2}}(\eta_N - \pi^0) & K^0 & D^- \\ K^- & \bar{K}^0 & \eta_S & D_S^- \\ \bar{D}^0 & D^+ & D_S^+ & \eta_c \end{pmatrix}, \quad (1)$$

and the matrix of scalar fields S (with quantum numbers $J^{PC} = 0^{++}$) reads

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\sigma_N + a_0^0) & a_0^+ & K_0^{*+} & D_0^{*0} \\ a_0^- & \frac{1}{\sqrt{2}}(\sigma_N - a_0^0) & K_0^{*0} & D_0^{*-} \\ K_0^{*-} & \bar{K}_0^{*0} & \sigma_S & D_{S0}^{*-} \\ \bar{D}_0^{*0} & D_0^{*+} & D_{S0}^{*+} & \chi_{c0} \end{pmatrix}, \quad (2)$$

which are used to construct the matrix $\Phi = S + iP$. In the pseudoscalar sector there are: an open charmed state $D^{0,\pm}$, open strange-charmed states D_S^\pm , and a hidden charmed ground state $\eta_c(1S)$. In the scalar sector there are open charmed $D_0^{*0,\pm}$ and strange charmed meson $D_{S0}^{*\pm}$ which are assigned to $D_0^*(2400)^{0,\pm}$ and $D_{S0}^*(2317)^\pm$, respectively.

We now turn to the vector sector. The matrix V^μ which includes the vector degrees of freedom is:

$$V^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(\omega_N + \rho^0) & \rho^+ & K^*(892)^+ & D^{*0} \\ \rho^- & \frac{1}{\sqrt{2}}(\omega_N - \rho^0) & K^*(892)^0 & D^{*-} \\ K^*(892)^- & \bar{K}^*(892)^0 & \omega_S & D_S^{*-} \\ \bar{D}^{*0} & D^{*+} & D_S^{*+} & J/\psi \end{pmatrix}^\mu, \quad (3)$$

where the nonstrange-charmed fields D^{*0} , $D^{*\pm}$ correspond to $\bar{q}q$ resonances $D^*(2007)^0$ and $D^*(2010)^\pm$, respectively, while the strange-charmed $D_0^{*\pm}$ is assigned to the resonance $D_0^{*\pm}$ (with mass $m_{D_0^{*\pm}}$), and there is the lowest vector charmonium state $J/\psi(1S)$.

The matrix A^μ describing the axial-vector degrees of freedom is given by:

$$A^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}(f_{1,N} + a_1^0) & a_1^+ & K_1^+ & D_1^0 \\ a_1^- & \frac{1}{\sqrt{2}}(f_{1,N} - a_1^0) & K_1^0 & D_1^- \\ K_1^- & \bar{K}_1^0 & f_{1,S} & D_{S1}^- \\ \bar{D}_1^0 & D_1^+ & D_{S1}^+ & \chi_{c,1} \end{pmatrix}^\mu, \quad (4)$$

where the open charmed mesons D_1 and D_{S1} are assigned to $D_1(2420)$ and $D_{S1}(2536)$, respectively, whereas the charm-anticharm state χ_{c1} corresponds to the $c\bar{c}$ resonance $\chi_{c1}(1P)$. From the matrices V^μ and A^μ we construct the left-handed and right-handed vector fields

$L^\mu = V^\mu + A^\mu$ and $R^\mu = V^\mu - A^\mu$, respectively.

The explicit form of the eLSM Lagrangian for $N_f = 4$ is analogous to the case $N_f = 3$ of Ref. [12, 13] (but has an additional term $-2 \text{Tr}[E\Phi^\dagger\Phi]$):

$$\begin{aligned} \mathcal{L} = & \frac{1}{2}(\partial_\mu G)^2 - V_{dil}(G) + \text{Tr}[(D^\mu\Phi)^\dagger(D^\mu\Phi)] - m_0^2 \left(\frac{G}{G_0}\right)^2 \text{Tr}(\Phi^\dagger\Phi) - \lambda_1[\text{Tr}(\Phi^\dagger\Phi)]^2 \\ & - \lambda_2 \text{Tr}(\Phi^\dagger\Phi)^2 + \text{Tr}[H(\Phi + \Phi^\dagger)] + \text{Tr}\left\{\left[\left(\frac{G}{G_0}\right)^2 \frac{m_1^2}{2} + \Delta\right] [(L^\mu)^2 + (R^\mu)^2]\right\} \\ & - \frac{1}{4}\text{Tr}[(L^{\mu\nu})^2 + (R^{\mu\nu})^2] - 2 \text{Tr}[E\Phi^\dagger\Phi] + c(\det\Phi - \det\Phi^\dagger)^2 + ic_{\tilde{G}\Phi}\tilde{G}(\det\Phi - \det\Phi^\dagger) \\ & + i\frac{g_2}{2}\{\text{Tr}(L_{\mu\nu}[L^\mu, L^\nu]) + \text{Tr}(R_{\mu\nu}[R^\mu, R^\nu])\} + \frac{h_1}{2}\text{Tr}(\Phi^\dagger\Phi)\text{Tr}[(L^\mu)^2 + (R^\mu)^2] \\ & + h_2\text{Tr}[(\Phi R^\mu)^2 + (L^\mu\Phi)^2] + 2h_3\text{Tr}(\Phi R_\mu\Phi^\dagger L^\mu) + \dots, \end{aligned} \quad (5)$$

where the field G denotes the dilaton field and its potential [19] reads

$$V_{dil}(G) = \frac{1}{4} \frac{m_G^2}{\Lambda_G^2} \left[G^4 \ln\left(\frac{G}{\Lambda_G}\right) - \frac{G^4}{4} \right], \quad (6)$$

in which the parameter $\Lambda_G \sim N_C \Lambda_{QCD}$ sets the energy scale of the gauge theory. The dilaton potential breaks the dilatation symmetry explicitly. $D^\mu\Phi \equiv \partial^\mu\Phi - ig_1(L^\mu\Phi - \Phi R^\mu)$ is the covariant derivative; $L^{\mu\nu} \equiv \partial^\mu L^\nu - \partial^\nu L^\mu$, and $R^{\mu\nu} \equiv \partial^\mu R^\nu - \partial^\nu R^\mu$ are the left-handed and right-handed field strength tensors. In eLSM Lagrangian (5) the dots refer to further chirally invariant terms listed in Ref. [12]: these terms do not affect the masses and decay widths studied in the present work and we therefore omitted them. The term $ic_{\tilde{G}\Phi}\tilde{G}(\det\Phi - \det\Phi^\dagger)$ describes the interaction between the pseudoscalar glueball $\tilde{G} \equiv |gg\rangle$ and (pseudo-)scalar mesons, which is used to study the phenomenology of the pseudoscalar glueball in the case of $N_f = 3$ [20]. The terms $\text{Tr}[H(\Phi + \Phi^\dagger)]$ with $H = 1/2 \text{diag}\{h_{0N}, h_{0N}, \sqrt{2}h_{0S}, \sqrt{2}h_{0C}\}$, $-2 \text{Tr}[E\Phi^\dagger\Phi]$ with $E = \text{diag}\{\varepsilon_N, \varepsilon_N, \varepsilon_S, \varepsilon_C\}$, $\varepsilon_i \propto m_i^2$, $\varepsilon_N = \varepsilon_S = 0$, and $\text{Tr}[\Delta(L^{\mu 2} + R^{\mu 2})]$ with $\delta = \text{diag}\{\delta_N, \delta_N, \delta_S, \delta_C\}$, $\delta_i \sim m_i^2$, $\delta_N = \delta_S = 0$, break chiral symmetry due to nonzero quark masses and are especially important for mesons containing the charm quark. When $m_0^2 < 0$ spontaneous symmetry breaking occurs and the scalar-isoscalar fields condense as well as the glueball field $G = G_0$. To implement this breaking we shift σ_N, σ_S, G , and χ_{C0} by their respective vacuum expectation values ϕ_N, ϕ_S, G_0 , and ϕ_C [16, 17, 18] as

$$\sigma_N \rightarrow \sigma_N + \phi_N, \quad \sigma_S \rightarrow \sigma_S + \phi_S, \quad G \rightarrow G + G_0, \quad \text{and} \quad \chi_{C0} \rightarrow \chi_{C0} + \phi_C. \quad (7)$$

Most of the parameters of the model were already fixed in the three-flavor study of Ref. [12]. Only three new parameters appear and all of them are related to the bare mass of the charm quark. They were determined in Ref. [16] through a fit to the masses of charmed mesons. As an outcome, the charm-anticharm condensate is sizable, $\phi_C = 178 \pm 28$ MeV.

3. Results

The weak-decay constants of the pseudoscalar open charmed mesons D and D_S [16, 17, 18] are

$$f_D = \frac{\phi_N + \sqrt{2}\phi_C}{\sqrt{2}Z_D} = (254 \pm 17) \text{ MeV}, \quad f_{D_S} = \frac{\phi_S + \phi_C}{Z_{D_S}} = (261 \pm 17) \text{ MeV},$$

where the experimental values [21] are

$$f_D = (206.7 \pm 8.9) \text{ MeV}, \quad f_{D_S} = (260.5 \pm 5.4) \text{ MeV}.$$

The results for the open charmed meson masses are reported in Table 1 [16, 17]. They have been obtained through a fit to experimental data

Table 1 : Masses of open charmed meson.

Resonance	Our Value [MeV]	Experimental Value[MeV]
D^0	1981 ± 73	1864.86 ± 0.13
D_S^\pm	2004 ± 74	1968.50 ± 0.32
$D_0^*(2400)^0$	2414 ± 77	2318 ± 29
$D_{S0}^*(2317)^\pm$	2467 ± 76	2317.8 ± 0.6
$D^*(2007)^0$	2168 ± 70	2006.99 ± 0.15
D_s^*	2203 ± 69	2112.3 ± 0.5
$D_1(2420)^0$	2429 ± 63	2421.4 ± 0.6
$D_{S1}(2536)^\pm$	2480 ± 63	2535.12 ± 0.13

The results of (OZI-dominant) strong decay widths of the open charmed mesons described by the resonances D_0^* , D^* , and D_1 are summarized in Table 2 [16, 18].

Table 2: Decay widths of charmed mesons

Decay Channel	Theoretical result [MeV]	Experimental result [MeV]
$D_0^*(2400)^0 \rightarrow D\pi$	139^{+243}_{-114}	full width $\Gamma = 267 \pm 40$
$D_0^*(2400)^+ \rightarrow D\pi$	51^{+182}_{-51}	full width: $\Gamma = 283 \pm 24 \pm 34$
$D^*(2007)^0 \rightarrow D^0\pi^0$	0.025 ± 0.003	< 1.3
$D^*(2007)^0 \rightarrow D^+\pi^-$	0	not seen
$D^*(2010)^+ \rightarrow D^+\pi^0$	$0.018^{+0.002}_{-0.003}$	0.029 ± 0.008
$D^*(2010)^+ \rightarrow D^0\pi^+$	$0.038^{+0.005}_{-0.004}$	0.065 ± 0.017
$D_1(2420)^0 \rightarrow D^*\pi$	65^{+51}_{-37}	full width: $\Gamma = 27.4 \pm 2.5$
$D_1(2420)^0 \rightarrow D^0\pi\pi$	0.59 ± 0.02	seen
$D_1(2420)^0 \rightarrow D^+\pi^-\pi^0$	$0.21^{+0.01}_{-0.015}$	seen
$D_1(2420)^0 \rightarrow D^+\pi^-$	0	not seen; $\Gamma(D^+\pi^-)/\Gamma(D^{*+}\pi^-) < 0.24$
$D_1(2420)^+ \rightarrow D^*\pi$	65^{+51}_{-36}	full width: $\Gamma = 25 \pm 6$
$D_1(2420)^+ \rightarrow D^+\pi\pi$	0.56 ± 0.02	seen
$D_1(2420)^+ \rightarrow D^0\pi^0\pi^+$	0.22 ± 0.01	seen
$D_1(2420)^+ \rightarrow D^0\pi^+$	0	not seen

4. Conclusion

In this work we have presented the outline of the extension of the eLSM from the three-flavor case to the four-flavor case including the charm quark has been presented. Most parameters are determined in the low-energy study for the nonstrange-strange sector [12]. Three new unknown parameters have been fixed in a fit to the experimental values (details are presented in Ref.[16]). The weak decay constants of nonstrange charm D and strange charm D_S have been calculated. The open charmed meson masses in the eLSM (5) have been computed, which being in reasonably good agreement with experimental data [21]. We have evaluated the (OZI-dominant) decays of open charmed mesons. The results are compatible with the results and the upper bounds listed by the PDG [21]. Moreover, the decay of the vector and axial-vector chiral partners $D^*(2010)$ and $D_1(2420)$ are well described. This fact shows that chiral symmetry is still important for charmed mesons.

Further applications of the described approach are to calculate the mixing of axial-vector and pseudovector charmed states and the decay widths of hidden charmed mesons into light mesons, scalar glueball, and pseudoscalar glueball. These works are currently in progress.

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References

- [1] H. -B. Li, Nucl. Phys. Proc. Suppl. **233**, 185 (2012) [arXiv:1209.3059 [hep-ex]].
- [2] H. Albrecht *et al.*, [ARGUS Collaboration], Phys. Lett. **B308**, 435 (1993); H. Muramatsu *et al.*, [CLEO Collaboration], Phys. Rev. Lett. **89**, 251802 (2002).
- [3] J. E. Bartelt, Annu. Rev. Nucl. Part. Sci. **45**, 133-61 (1995); A. Anastassov *et al.* [CLEO Collaboration], Phys. Rev. D **65**, 032003 (2002) [hep-ex/0108043].
- [4] S. Godfrey and I. Isgur, Phys. Rev. D **32** (1985) 189; S. Godfrey and R. Kokoski, Phys. Rev. D **43**, 1679 (1991).
- [5] S. Capstick and N. Isgur, Phys. Rev. D **34** 2809 (1986); N. Isgur and M. B. Wise, Phys. Rev. Lett. **66**, 1130 (1991); E. J. Eichten, T. Hill and C. Quigg, Phys. Rev. Lett. **71** 4116 (1994); E. J. Eichten, T. Hill and C. Quigg, FERMILAB-CONF-94/118-T; Z. Maki and I. Umemura, Prog. Theor. Phys. **59** 507 (1978).
- [6] G. S. Bali, Int. J. Mod. Phys. A **21** 5610 (2006) [hep-lat/0608004]; M. Kalinowski and M. Wagner, PoS ConfinementX, 303 (2012) [arXiv:1212.0403 [hep-lat]].
- [7] M. Neubert, Phys. Rept. **245**, 259 (1994) [hep-ph/9306320]; R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio and G. Nardulli, Phys. Rept. **281**, 145 (1997) [hep-ph/9605342]; H. Georgi, Phys. Lett. B **240**, 447 (1990); M. B. Wise, Phys. Rev. D **45**, 2188 (1992).
- [8] C. Amsler and N.A. Tornqvist, Phys. Rept. **389**, 61 (2004); E. Klemt and A. Zaitsev, Phys. Rept. **454**, 1 (2007) [arXiv: 0708.4016[hep-ph]].
- [9] J.T. Lenaghan, D.H. Rischke and J. Schaffner-Bielich, Phys. Rev. D **62**, 085008 (2000) [nucl-th/0004006].
- [10] M. Bando, T. Kugo and K. Yamawaki, Phys. Rept. **164**, 217 (1988); G. Ecker, J. Gasser, A. Pich and E. de Rafael, Nucl. Phys. **B321**, 311 (1989); E.E. Jenkins, A.V. Manohar and M.B. Wise, Phys. Rev. Lett. **75**, 2272 (1995) [arXiv:hep-ph/9506356].
- [11] D. Parganlija, F. Giacosa and D. H. Rischke, Phys. Rev. D **82**, 054024 (2010) [arXiv:1003.4934 [hep-ph]]; S. Gallas, F. Giacosa and D. H. Rischke, Phys. Rev. D **82**, 014004 (2010) [arXiv:0907.5084 [hep-ph]].
- [12] D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa and D. H. Rischke, Phys. Rev. D **87**, 014011 (2013) [arXiv:1208.0585 [hep-ph]].
- [13] F. Giacosa, D. Parganlija, P. Kovacs and G. Wolf, EPJ Web Conf. **37**, 08006 (2012) [arXiv:1208.6202 [hep-ph]]; D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa and D. H. Rischke, Acta Phys. Polon. Supp. **5**, 1109 (2012) [arXiv:1208.2054 [hep-ph]].
- [14] G. t Hooft, Phys. Rev. D **14**, 3432 (1976); G. t Hooft, Phys. Rev. Lett. **37**, 8 (1976); G. t Hooft, Phys. Rept. **142**, 357 (1986).
- [15] C. Vafa and E. Witten, Nucl. Phys. B **234**, 173 (1984); L. Giusti and S. Necco, JHEP **0704**, 090 (2007) [hep-lat/0702013 [HEP-LAT]].
- [16] W. I. Eshraim, F. Giacosa and D. H. Rischke, arXiv:1405.5861 [hep-ph].
- [17] W. I. Eshraim, PoS QCD -TNT-III, 049 (2013) [arXiv:1401.3260 [hep-ph]].
- [18] W. I. Eshraim and F. Giacosa, arXiv:1409.5082 [hep-ph]; W. I. Eshraim, arXiv:1411.2218 [hep-ph].
- [19] A. Salomone, J. Schechter and T. Tudron, Phys. Rev. D **23**, 1143 (1981); H. Gomm and J. Schechter, Phys. Lett. B **158**, 449 (1985); A. A. Migdal and M. A. Shifman, Phys. Lett. B **114**, 445 (1982).
- [20] W. I. Eshraim, S. Janowski, F. Giacosa and D. H. Rischke, Phys. Rev. D **87**, 054036 (2013) [arXiv:1208.6474 [hep-ph]]; W. I. Eshraim, S. Janowski, A. Peters, K. Neuschwander and F. Giacosa, Acta Phys. Polon. Supp. **5**, 1101 (2012) [arXiv:1209.3976 [hep-ph]]; W. I. Eshraim and S. Janowski, PoS ConfinementX **118**, (2012) [arXiv:1301.3345 [hep-ph]]; W. I. Eshraim and S. Janowski, J. Phys. Conf. Ser. **426**, 012018 (2013) [arXiv:1211.7323 [hep-ph]].
- [21] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86**, 010001 (2012).